Enabling Research for the Future Electric Energy Grid – NSF Role

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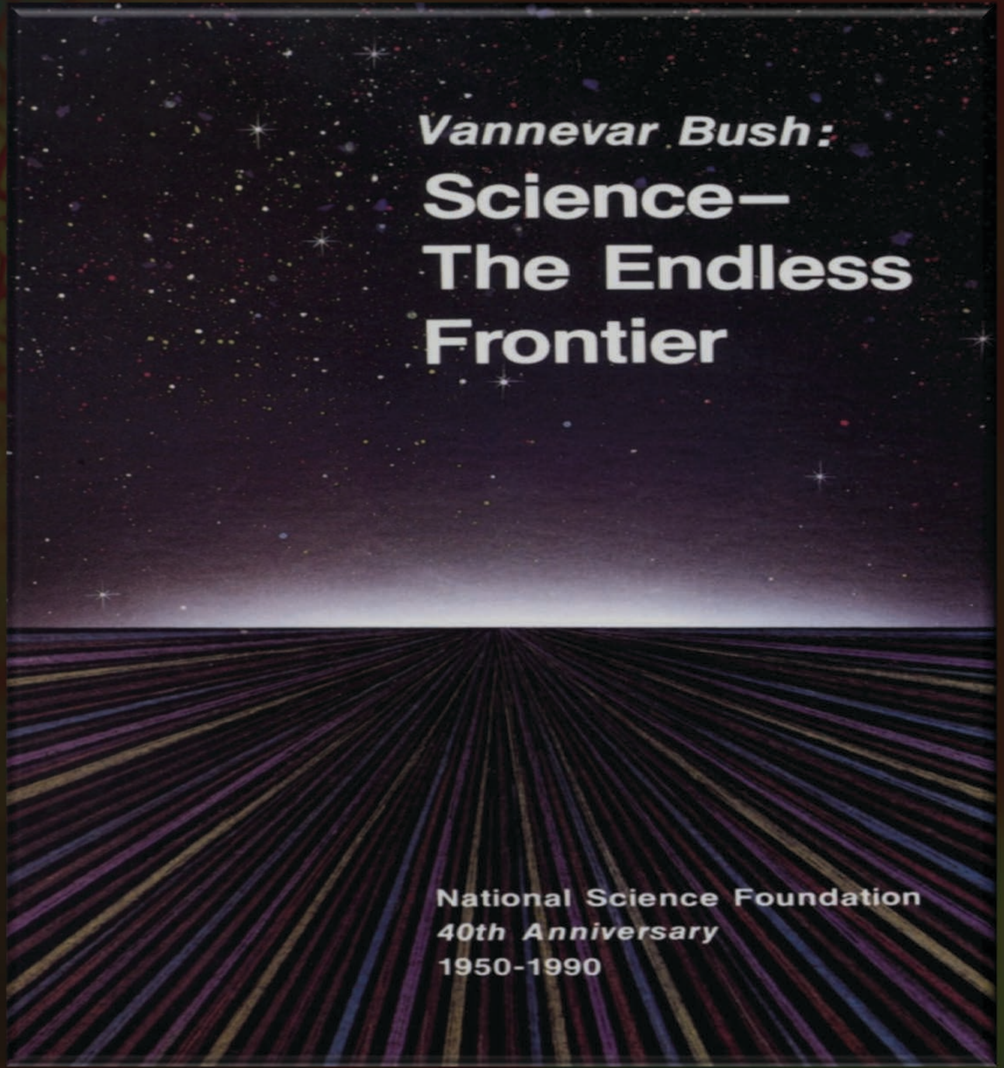
Outline

- Introduction to NSF
- Context and Drivers for Smart Grid
- Relevant NSF Programs
- Conclusion

Image courtesy MIT Museum



"to promote the progress of science; to advance the national health, prosperity, and welfare; to secure the national defense…"

NSF Act, 1950

Directorate for Engineering

Fundamental

EFRI

CBET

- Chemical & Biochemical Systems
- Bioengineering and Engineering Healthcare
- Environmental Engineering and Sustainability
- Transport, Thermal, & Fluid Phenomena

CMMI

- Advanced Manufacturing
- Mechanics and Engineering Materials
- Resilient and Sustainable Infrastructure
- Operations Design and Dynamical Systems

ECCS

- Electronics, Photonics, and Magnetic Devices
- Communications, Circuits, and Sensing Systems
- Energy, Power, Control and Networks

EEC

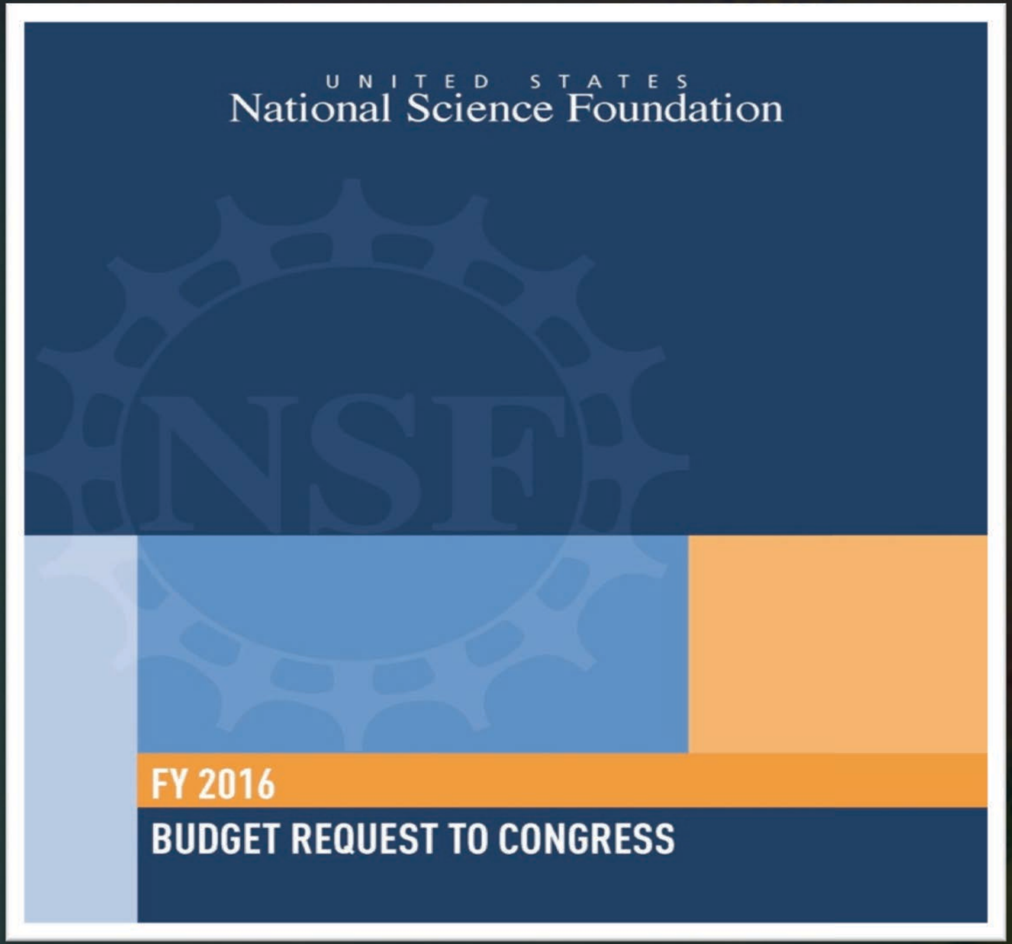
- Engineering Research Centers
- Engineering Education
- Engineering Workforce

Translational

IIP

- Academic Partnerships
- Small Business Partnerships

FY 2016 Budget Request



NSF

- FY 2016 Budget Request: $7723.55 Million
- Increase over FY 2015 Est: $379.34 Million, +5.2%

ENG

	FY 2014 Actual*	FY 2015 Current Plan	FY 2016 Request	Change over FY 2015 Current Plan	
				Amount	Percent
CBET	$167.76	$177.82	$192.26	$14.44	8.1%
CMMI	195.23	209.52	222.73	13.21	6.3%
ECCS	100.37	110.43	119.24	8.81	8.0%
EEC	119.50	117.49	110.39	-7.10	-6.0%
IIP	205.99	226.98	248.11	21.13	9.3%
SBIR/STTR	*159.99*	*177.11*	*194.36*	*17.25*	*9.7%*
EFMA	44.27	50.07	56.49	6.42	12.8%
ENG TOTAL	$833.12	$892.31	$949.22	$56.91	6.4%

Drivers for Change

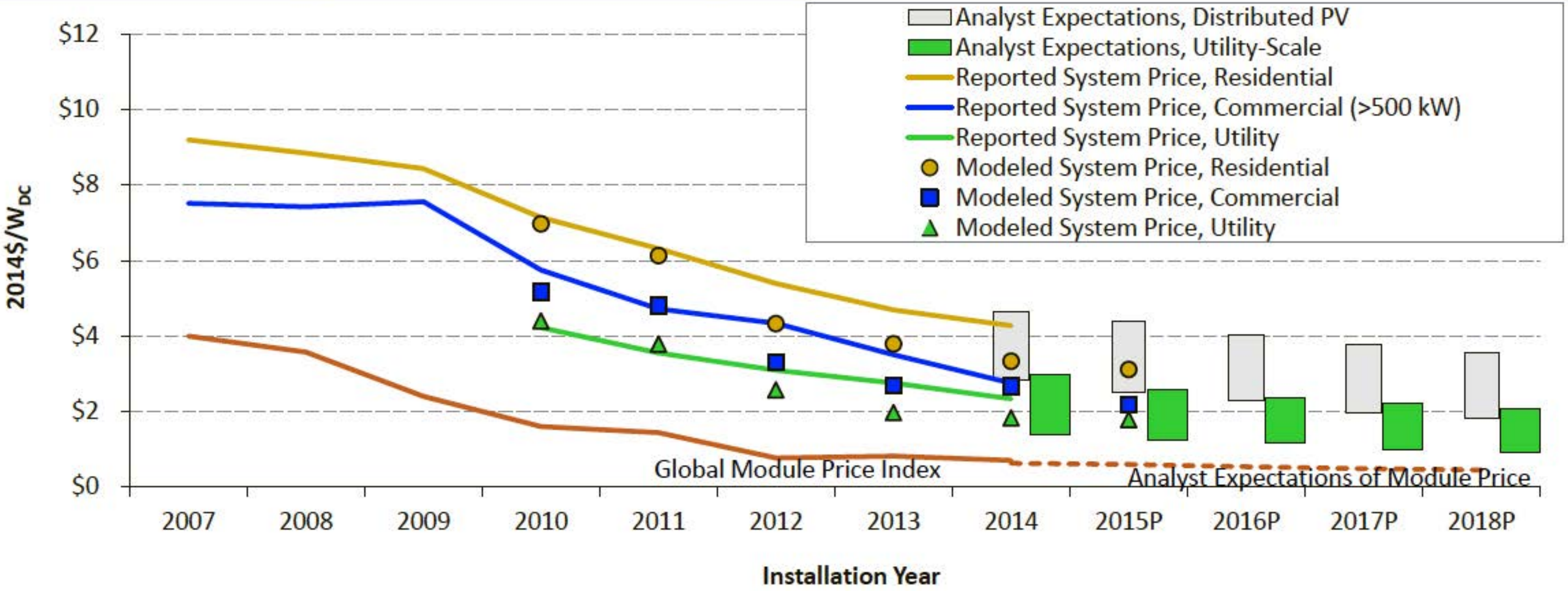
- Aging infrastructure
- Renewable electricity integration
- Energy efficiency
- Grid security and reliability
- Grid transformation – smart grid
- Demand side management and consumer participation
- Evolving regulation

Aging Grid Infrastructure

- Transmission and distribution infrastructure is aging in the US
- More than 70% of transmission lines and transformers are 25 years or older
- More than 65% of circuit breakers are 25 years or older
- 25-35% of generation and transmission nearing end of useful life and 8% are already beyond useful life
- Almost 50% of GT assets will be replaced by 2030
- Cost of power outages and quality to US economy ~$120-190B
- *Total investment to 2030 ~ $975B*

Source: Black and Veatch, 2009
Primen, The Cost of Power Disturbances to Industrial & Digital Economy Companies, EPRI, 2001

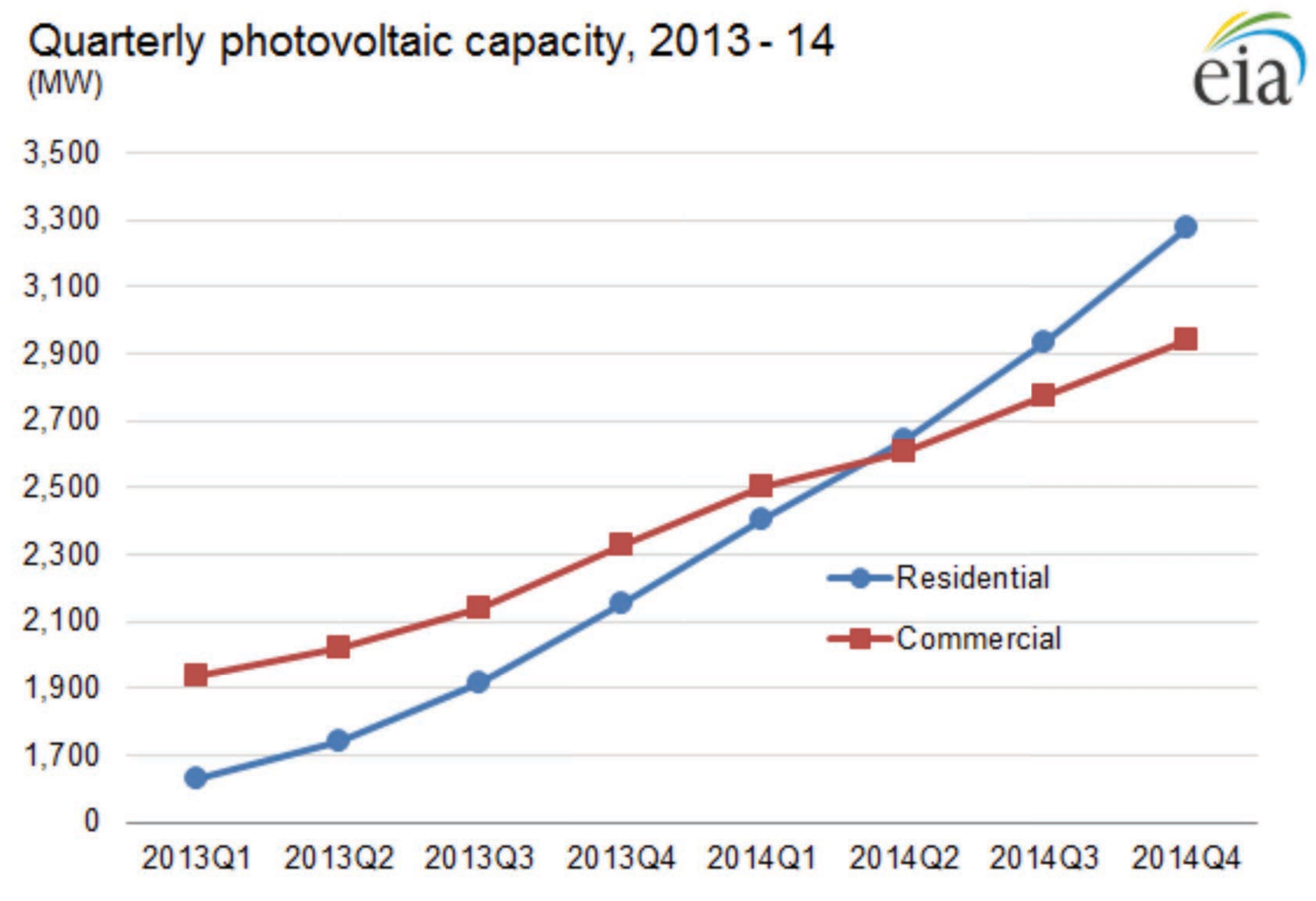
Reported, Bottom-up, and Analyst-Projected Average U.S. PV System Prices over Time



- All methodologies show a downward trend in PV system pricing
- Reported pricing and modeled benchmarks historically had similar results; however, they have recently diverged in estimated pricing.

Source: DOE

PV Residential and Commercial Capacity

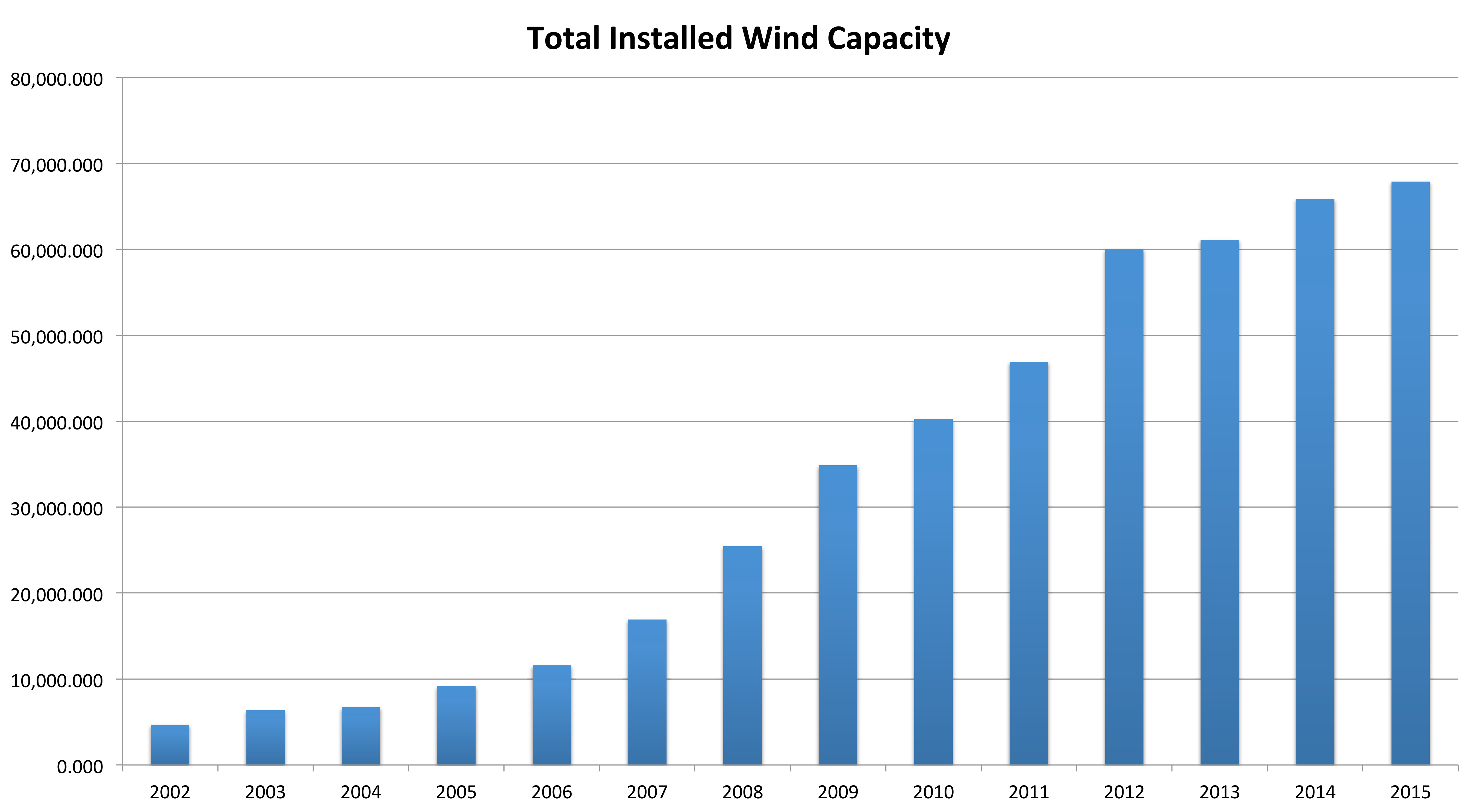


Source: U.S. Energy Information Administration

PV: Utility Scale vs Residential

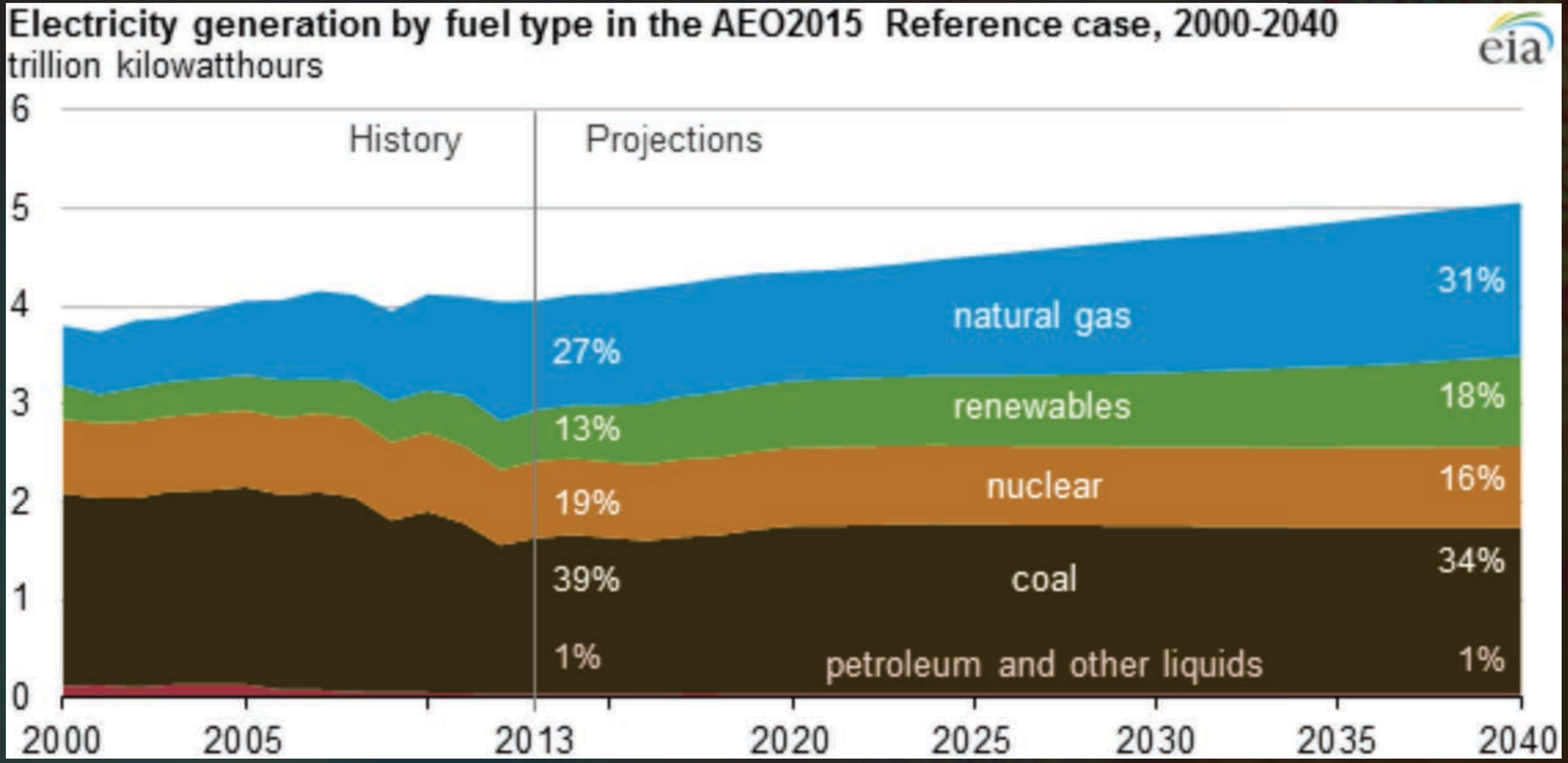
- PV Generation costs:
  - residential-scale systems: 16.7¢/kWh
  - utility-scale PV systems: 8.3¢/kWh)
- Reasons for this gap:
  - lower total plant costs per installed kilowatt for larger facilitie
  - greater solar electricity due to optimized panel orientation and tracking;
  - other economies of scale and efficiencies
- Avoided transmission and distribution costs by residential-scale systems are not large enough to significantly impact this gap in generation costs.

Source: Brattle Group 2015


Total Installed Wind Capacity
80,000.000
70,000.000
60,000.000
50,000.000
40,000.000
30,000.000
20,000.000
10,000.000
0.000
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015

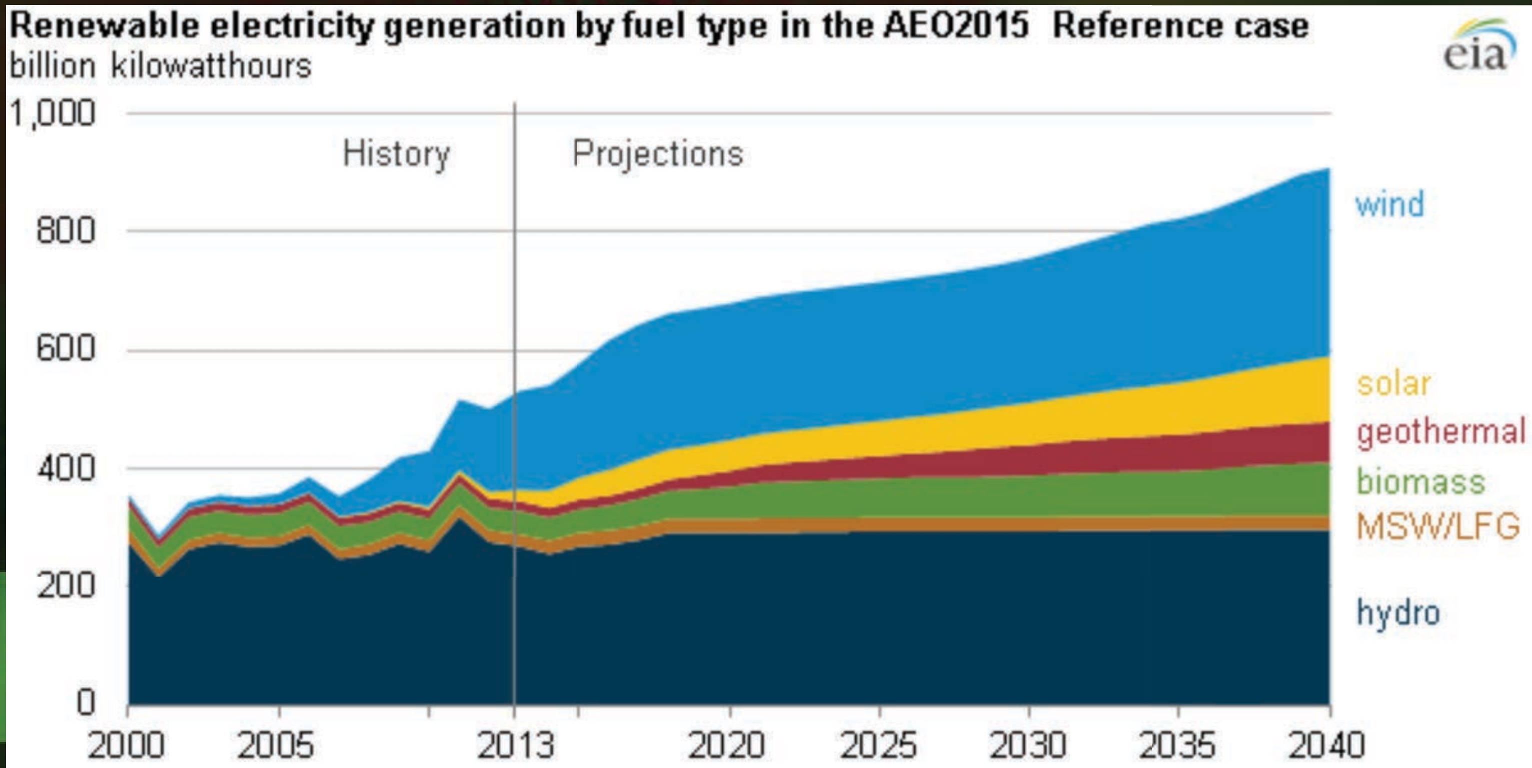
Source: DOE

Electricity Projections



Source: U.S. Energy Information Administration, AEO 2015

Renewables

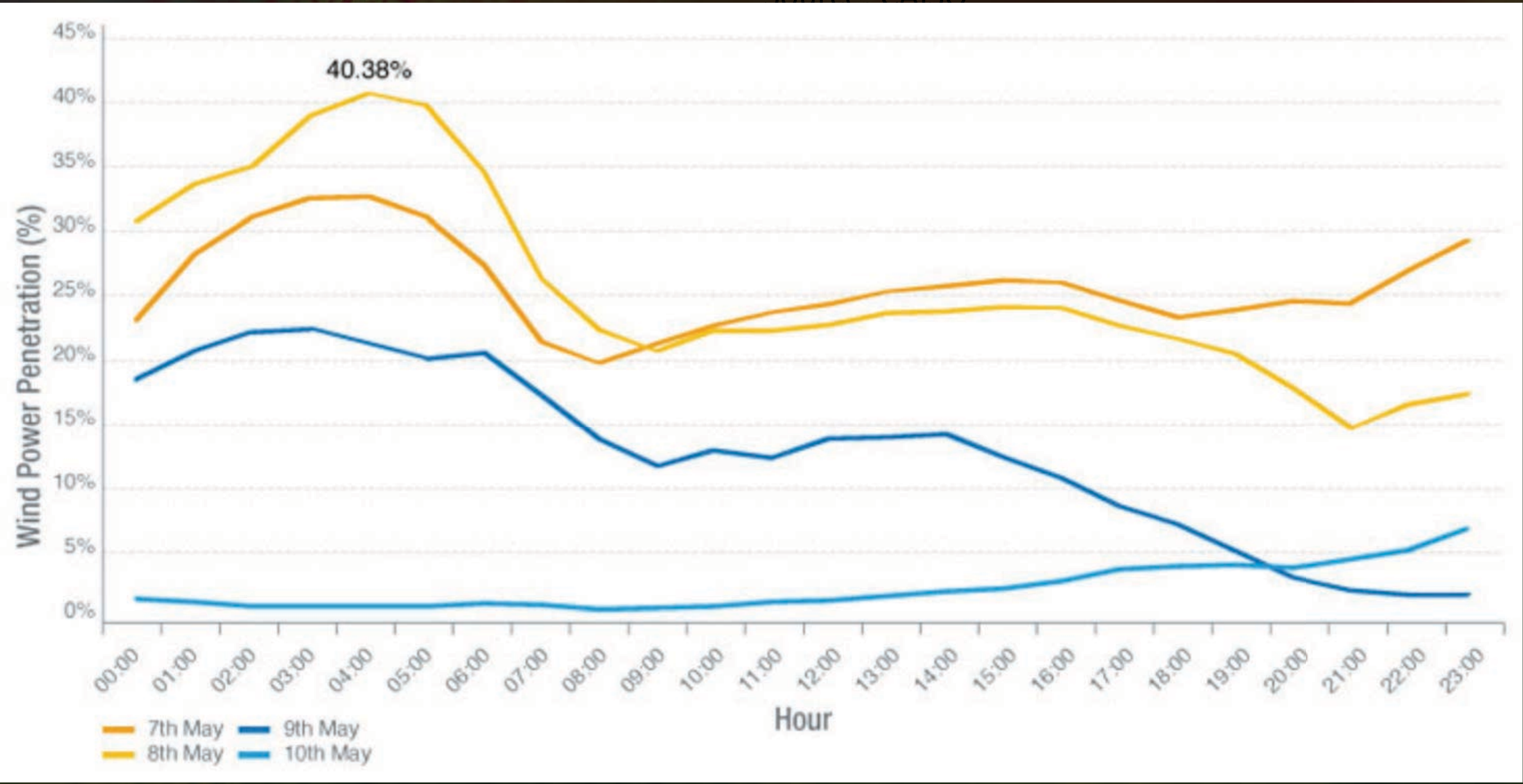


Variability of Wind and Solar

- Power output varies in all time frames:
  - Annual
  - Seasonal
  - Daily
  - Hours
  - Minutes
  - Seconds

Hourly wind penetration in Ireland May 7–10, 2009

Source: CAISO



Source: NREL

Intermittency, uncontrollability, and uncertainty - principal causes of difficulty at the operational level in integration of wind and solar into the grid.

Energy Efficiency

- Globally, more than 2/3 of potential efficiency gains still remains untapped to 2030
  - >80%unrealized potential in buildings
  - 80% unrealized potential in electricity generation
  - 55% unrealized in industry
- Large potential opportunity

Source: IEA, WEO 2015

Electricity System R&D Needs

- Develop and refine interoperable grid architectures and new system designs
- Develop software and visualization tools that use new data from transmission and distribution system devices for enhanced, real-time operations and control
- Research material innovations and develop transmission and distribution component designs for higher performance, reliability, and resilience
- Embed intelligence, communication, and control capabilities into distributed energy resources and systems such as microgrids to support grid operations

Source: DOE: Quadrennial Energy Review, 2015

Electricity System R&D Needs

- Improve energy storage capabilities and systems designs that lower costs while increasing capacity and performance, and facilitating integration
- Develop high-fidelity planning models, tools, and simulators and a common framework for modeling, including databases
- Design innovative technologies and resilient and adaptive control systems to improve physical- and cyber-security of the grid

Source: DOE: Quadrennial Energy Review, 2015

Technological Drivers

- Decreasing cost of solar PV
- Novel power electronics devices with significant new capabilities
- Growing deployment of synchrophasors
- Distribution system automation
- Infusion of computing, communications and controls into the physical power system – smart grid
- Electric energy storage
- Electric and hybrid vehicles
- Fuel cells
- Natural gas stirling engines - micro generation

"Solar Power Battle Puts Hawaii at Forefront of Worldwide Changes"

NYT, April 2015

How can (will) the electric grid be transformed into a sustainable, reliable, and economic electric energy system for society?

Key Federal Agencies

- Department of Energy
  - OE, EERE, ARPA-E, BES
- Department of Defense
- NIST
- NSF

What is NSF enabling for the Emerging Power Grid?

Key NSF Programs

- Energy, Power, Controls and Networks (EPCN)
- Cyber-Physical Systems (CISE+ENG)
- Critical Resilient Infrastructure Systems and Processes (CRISP)
- Renewable electricity DCL

Energy, Power, Controls and Networks

EPCN places emphasis on electric power systems:

– generation, transmission, storage, and integration of renewables;
– power electronics and drives;
– battery management systems;
– hybrid and electric vehicles;
– power systems and associated regulatory and economic structures and consumer behavior.

Toward Grid-Interactive Converters with Diagnostic, Remedial, and Lifetime Prognostic Features for the Next Generation of Power Grids, Mirafzal, Kansas State, CAREER Award

- Create intelligent-reconfigurable grid-interactive solid-state converters as smart elements for the smart grid concept
- Advance availability and reliability of solid-state converters in wind and solar energy conversion systems
- Impart required knowledge and skills of practical problems of sustainable energy systems to the next generation of U.S. power engineers.

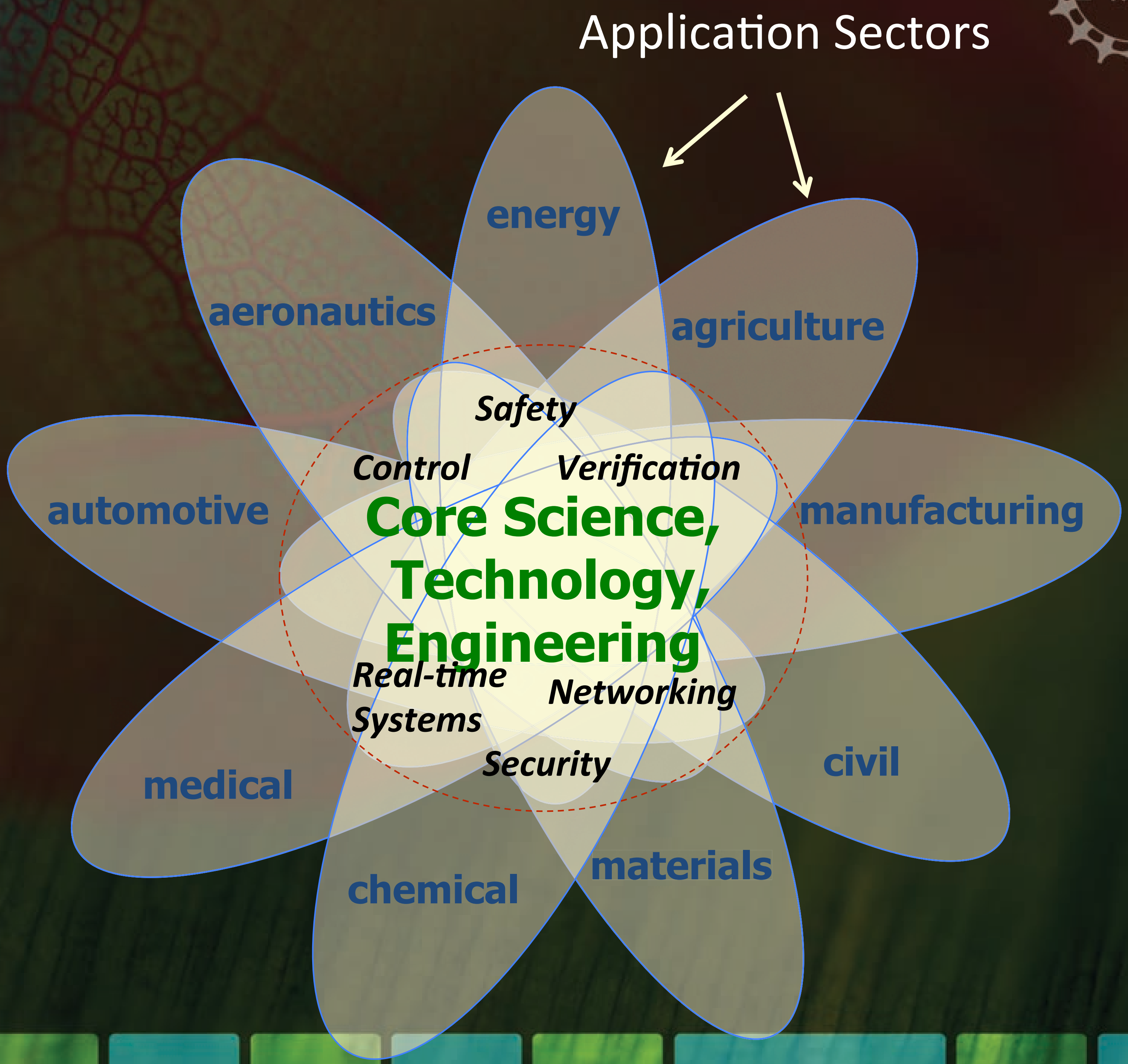
Cyber-Physical Systems (CPS)

- Roots in Cybernetics: idea goes back to Norbert Wiener
- Computation, communications, networking elements being increasingly infused into the physical world
- Computer science disciplines converging with disciplines that govern physical (and biological) worlds at multiple temporal and spatial scales
- *Internet-of-Things or Industrial Internet*

Transportation	▪**Faster and safer aircraft** ▪**Improved use of airspace** ▪**Safer, more efficient cars**
Energy and Industrial Automation	▪**Homes and offices that are more energy efficient and cheaper to operate** ▪**Distributed micro-generation for the grid**
Healthcare and Biomedical Systems	▪**Increased use of effective in-home care** ▪**More capable devices for diagnosis** ▪**New internal and external prosthetics**
Critical Infrastructure	▪**More reliable power grid** ▪**Highways that allow denser traffic with increased safety**

CPS Approach

- Abstract from application sectors to more foundational principles
- Apply these principles to problems in new sectors
- Safe, secure, reliable, verification, real-time adaptation, …



Federal Government-Wide Effort

- Cyber-Physical Systems Working Group
  - under NITRD (The Networking and Information Technology Research and Development Program)
- Co-chaired by NIST and NSF and includes DOD, NIH, NTIA, DOT, FDA, …
- At NSF: CISE and ENG Directorates
  - ECCS Division plays a key role in CPS in ENG

CPS program has funded numerous projects in electic grid research

Critical Infrastructure Sectors

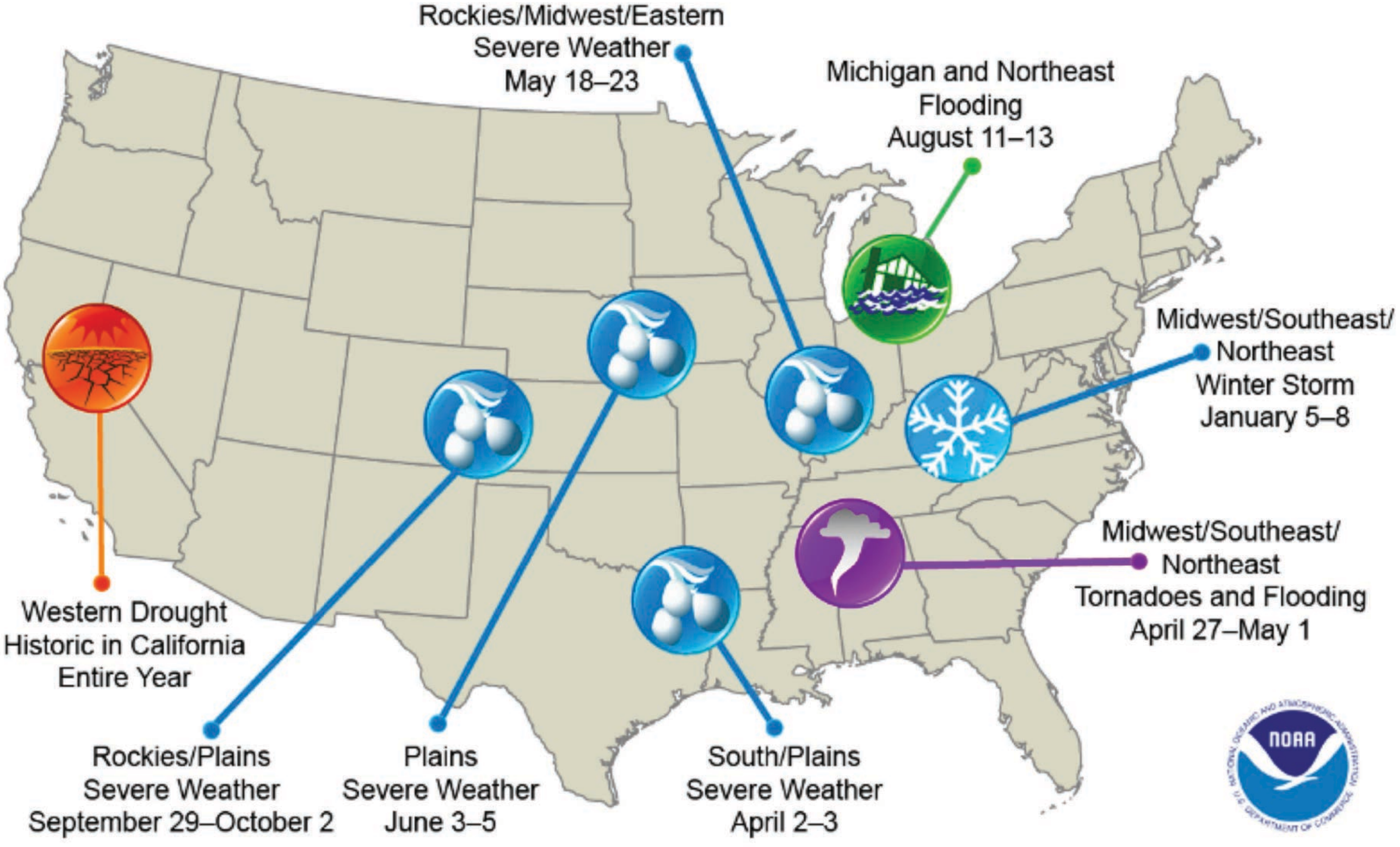
US DHS: National Infrastructure Protection Program (NIPP)

http://testdhsgov.edgesuite.net/files/programs/gc_1189168948944.shtm

Source: DHS

Critical Infrastructures are a mainstay of the national economy, security and societal functioning

U.S. 2014 Billion-Dollar Weather and Climate Disasters



This map denotes the approximate location for each of the eight billion-dollar weather and climate disasters that impacted the United States during 2014.

FY14: Resilient Interdependent Infrastructure Systems (RIPS)

- To enhance understanding and design of interdependent critical infrastructure systems and processes resilient in the face of disruptions and failures from any cause
- ENG, CISE, and SBE funded 10 projects for $17M in FY 2014

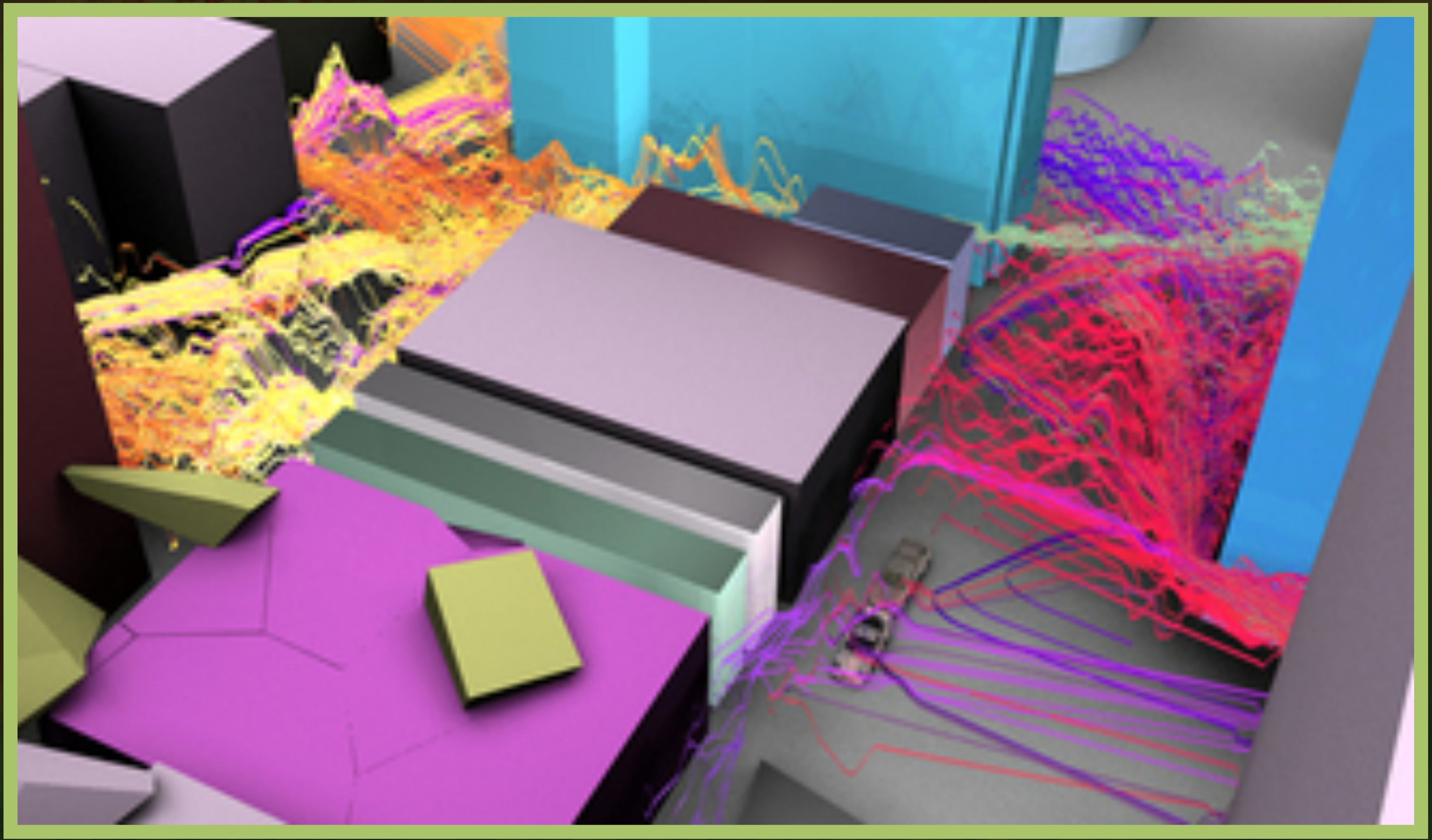


Image credit: Paul M. Torrens, Geography and UMIACS, University of Maryland, College Park

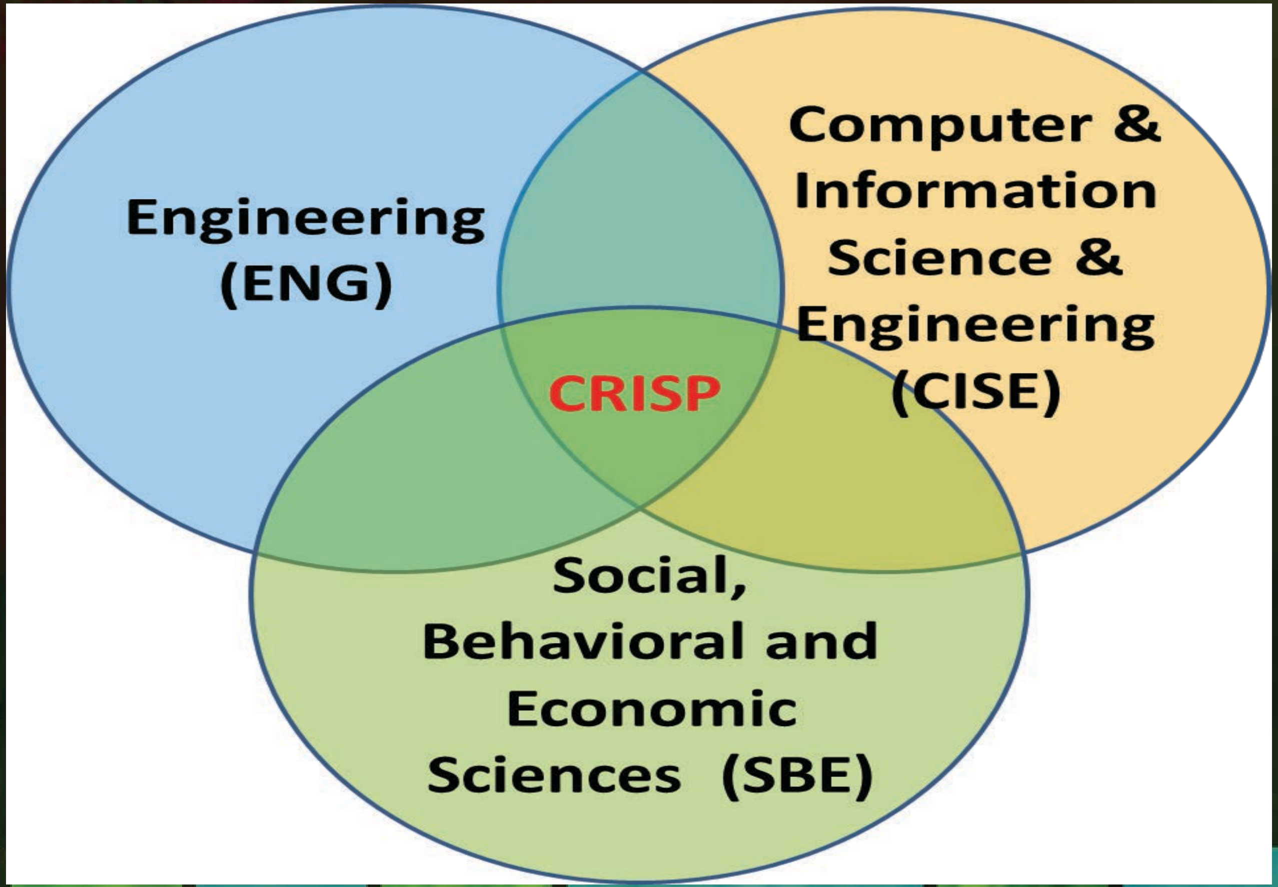
http://www.nsf.gov/news/news_summ.jsp?cntn_id=132852&org=NSF&from=news

Selected RIPS Awards

- “Towards resilient computational models of electricity-gas ICI”
- “Strategic Analysis and Design of Robust and Resilient Interdependent Power and Communication Networks”
- “Water and Electricity Infrastructure in the Southeast (WEIS) - Approaches to Resilient Interdependent Systems under Climate Change”
- “Resilience Simulation for Water, Power & Road Networks”

FY15 CRISP: Critical Resilient Interdependent Infrastructure Systems & Processes

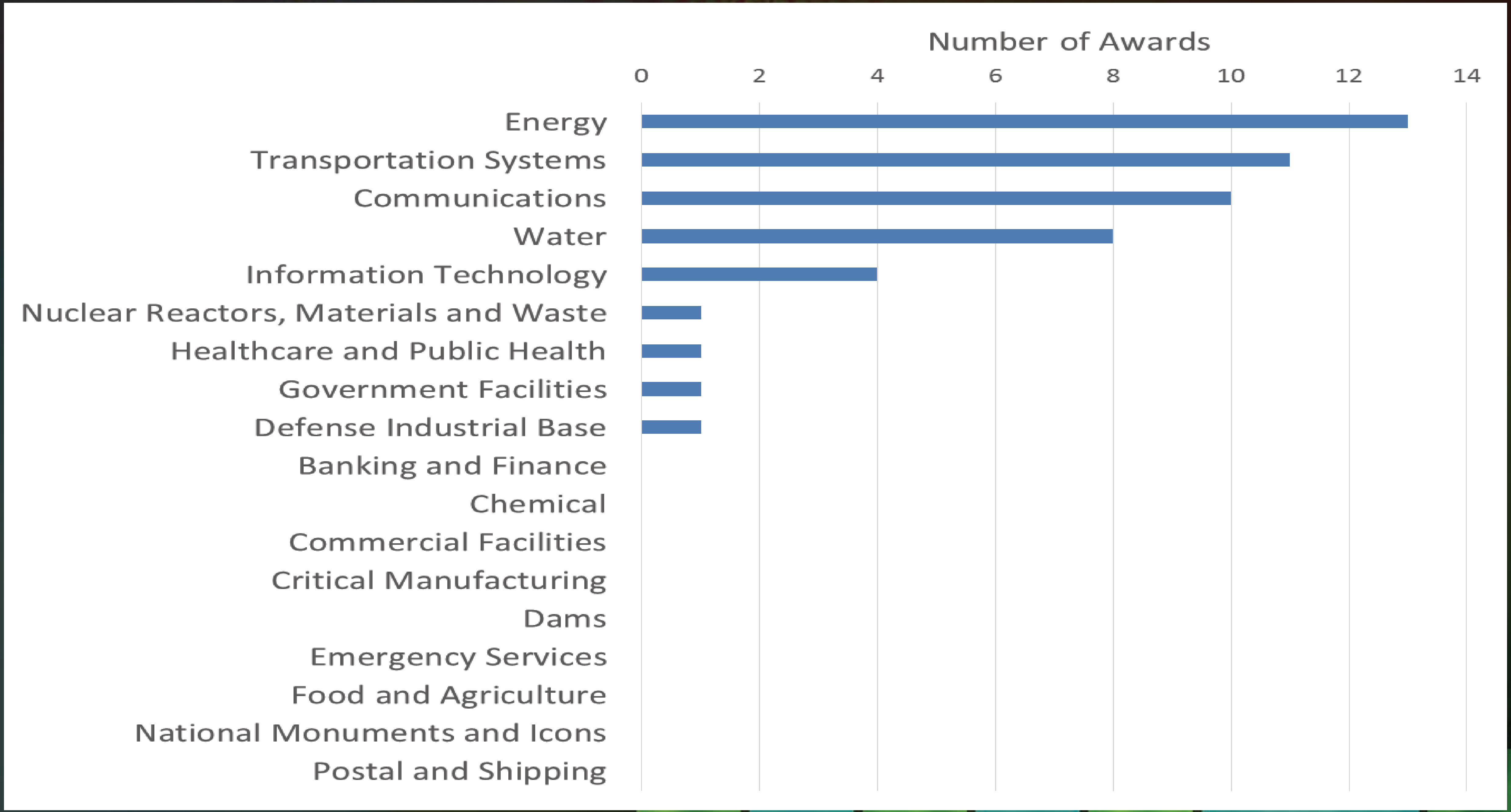
- FY15 funding for CRISP: $20 million
  - *Type 1 Awards*: 3-year projects, $500k max
  - *Type 2 Awards*: 3-4 year projects, $1M-$2.5M



CRISP Program Goals

1. Create new approaches/solutions for design/operation of infrastructures as processes/services
2. Enhance understanding/design of ICIs and processes under disruptions from any cause
   - natural, technological, organizational or malicious
   - various timescales and intensities
3. Create knowledge for innovation in ICIs to safely, securely, and effectively expand range of goods and services they enable
4. Improve ICI's effectiveness, efficiency, dependability

Targeted Infrastructures in the Awards



ECCS: Renewables DCL

- NSF 15-082: "Dear Colleague Letter: Research on Theory and Analytical Tools for Power Networks with High Levels of Renewable Generation"
- Competition for EAGER grants
- Purpose: support creative ideas addressing the continuing rise of renewable electric power generation.

Motivations

- Does large penetration of renewables affect power quality & grid stability? If so, what needs to be done? New policy? New automation?
- Are current market mechanisms appropriate going forward?
  - What policies should be in place to avoid undesired economic consequences of the evolution to the next generation grid?
- Do protection systems need redesign as the penetration of renewables increases?

Renewables DCL: Proposals

- NSF received 86 unique proposals in response to the Renewables DCL, representing 104 universities (including collaborative proposals).

Areas Targeted by the Proposals

- Control and system dynamics
- Electricity market design
- Analytical tools for system flow analysis
- Power electronics developments
- Generation and load scheduling
- Game theory/human behavior studies
- Fault diagnosis systems and devices
- Contingency analysis
- Optimization including distributed energy storage

Funded Proposal Topics (14 Grants)

- Grid stability analysis techniques with stochastic renewables (Mathieu; Chow).
- Policy issues for long term planning of the transition from thermal-dominated electric energy systems to a renewable-dominated design (Conejo; Tong).
- Stochastic optimization/mixed-integer programming for topology control of future grid (Oren/Sen)
- Design of new market mechanisms (Gupta/Turitsyn; Li; Poolla; Parvania/Scaglione; Zhu)
- Prosumer-centric energy management incorporating behavior modeling (Xie; Saad/Poor/Mandayam) – including use of Nobel prize winning "prospect theory" methodology by the latter team.
- Applying allometry (development of biological shapes) to understanding of power distribution network structure (Dobson).
- New framework for power system protection (Santoso).

Fundamental allometric scalings for distribution networks with renewables, Ian Dobson, Iowa State University

- Challenge: Design next generation distribution grid including significant renewable energy sources.
- Novelty:
  - Complex system network science for engineered distribution networks so that they can be optimally redesigned to accommodate renewables.
  - Idea of Allometry: study of how processes scale with body size and with each other, and the impact this has on ecology and evolution.
  - Integration of discovery of new theory with field data and engineering design.

Demand response algorithms to improve electric power system stability margins, Mathieu, University of Michigan, Ann Arbor

- Challenge: Develop systematic demand response (DR) methods to coordinate the demand of flexible loads to improve grid stability margins in systems with high penetrations of renewables. Stability margins are hard to compute, involve nonconvex problems.

- Expected Impact: Better demand response algorithms for systems with high penetration of renewables, respecting stability of overall system.

- Novelty: Formulating and solving the "spatial DR problem," i.e., optimal reallocation of load within a power system to achieve stability margin improvements subject to power network constraints and flexible load constraints.

Supply Rate Control and Grid Stability with Renewable Power Generation and Co-located Storage, Chow, RPI

- Challenge: How should renewable operators determine optimal contracts while minimizing storage? How can decentralized controllers be designed for frequency regulation and satisfactory transients?

- Expected Impact: Extend optimal power flow problems to a distributed framework with geographically disperse, heterogeneous renewable sources.

- Novelty:
  - Optimization modeling taking into account both day-ahead and real-time market electricity prices, forecast of renewable generation, network constraints, and storage limits.
  - Innovation of randomized control for decentralized frequency regulation.

Game-Theoretic Methods for Analysis and Design of Distributed Renewable-Based Energy, Zhu, NYU

- Challenge: Design electricity pricing for the electric grid with high penetration of renewable energy sources
- Novelty:
  - Model includes fluctuating electricity prices and availability of energy storing devices such as batteries to independent power producers.
  - Using locally situated batteries, renewable generation sources can game the system to maximize an expected benefit.

Market Mechanism for Managing Uncertainties Caused by High Levels of Renewable Generation, Li, IIT

- Challenge: Explore a fundamental market-based mechanism for grid addressing the uncertainty from renewable energy sources.

- Expected Impact: Incentives for renewable operators to improve forecasting accuracy; and for existing flexible resources. Provide price signals for siting new flexible resources to accommodate uncertainties.

- Novelty: Develop explicit price signals and a market mechanism to manage uncertainty using a robust optimization framework.

Toward Renewable Dominated Electric Energy Systems (RENDES),

Conejo, Ohio State University

- Challenge: Create mathematical models to analyze the transition from today's electric power systems to a future renewable-dominated design.
- Expected Impact The project can have significant impact on planning for a future grid with increasing levels of renewable generation.
- Novelty:
  - Integrated suite of short-run operational and long-run dynamic capacity expansion models.
  - Decomposition techniques to make the resulting stochastic programming, complementarity, and adaptive robust optimization models tractable.

A Dynamical Systems Approach to Modeling and Controlling Price Responsive Demand, Xie, Texas A&M

- Challenge: Develop dynamic systems models for demand response using empirical data
- Expected Impact: Provide insights into how independent system operators can incorporate demand response into their considerations.
- Novelty: New perspective on modeling the dynamical response of consumer behavior subject to incentives and other influence variables

Market Designs for Distribution Systems with High Renewable Penetration, Gupta & Turitsyn, Notre Dame & MIT

- Challenge: Construct a distribution-level energy market incorporating aggregators, considering impact of information asymmetry, limited computational capabilities, and effect on stability of the grid.
- Expected Impact: Creation of aggregator gateways for market participation of small prosumers for economic large scale renewable integration.
- Novelty: Mechanism design technique for the design of distribution markets for prosumers via aggregators.

Selling Demand Flexibility in The Future Electricity Grid

Poolla, UC Berkeley

- Challenge: Develop an economically sound approach to flexibility in demand response.
- Expected Impact: Systematic tools for developing pricing models for demand response services for future grid.
- Novelty: Demand response is viewed as a service to achieve various requirements such as power balancing and controlling transmission line congestion.

Foundations of Prosumer-Centric Grid Energy Management

Saad, Poor & Mandayam, Virginia Tech, Princeton & Rutgers

- Challenge: Study the foundations of prosumer-centric grid energy management.
- Expected Impact: Understanding prosumer behavior considering prosumers' appreciation of effects of their behavior.
- Novelty: A prosumer-centric energy management system based on a game-theoretic framework that integrates prospect theory and realistic behavior modeling.

Engineering Research Centers

- Future Renewable Electric Energy Delivery and Management Systems Center (FREEDM)
- Center for Ultra-Wide Resilient Electric Energy Transmission Networks (CURENT) – joint with DoE
- Quantum Energy and Sustainable Solar Technologies (QUEST)- joint with DoE
- Smart Lighting
- New ERC Competition *underway*

Industry-University Cooperative Research Centers

- Power Systems Engineering Research Center (PSERC)
- Energy-Smart Electronic Systems (ES2)
- Energy Harvesting Materials and Systems (CEHMS)
- Grid-Connected Advanced Power Electronic Systems (GRAPES)
- Advanced Vehicle and Extreme Environment Electronics (CAVE3)
- Novel High-V/T Materials and Structures (HVT)
- Next Generation Photovoltaic
- Silicon Solar Consortium
- Wind Energy Science, Technology and Research (WindSTAR)

Power Systems Education

- PSERC has a strong effort on power systems education
- CUSP at the University of Minnesota has made very strong efforts on making large amount of educational material available
- Similar efforts globally

Conclusion

NSF playing a key role in fundamental research to enable future electric grid

QUESTIONS?

IDEAS, THOUGHTS!

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